MOSCOW INSTITUTE OF PHYSICS AND TECHNOLOGY.

The World's Smallest Radio

By Ed Regis.

Based on

"Scientific American", March 2009, page 40-45.

PERFORMED BY

Lashkov Vladimir , gr. 615

Moscow, 23 May, 2009

Abstract.

This article tells us that label "nano" has been applied to items of many sort for years, but the first functioning nanoscale device – one that would have a measurable effect on macroscale world – proved to be a radio. It is said that this radio was able to play songs, like Eric Clapton's "Layla" using just a battery and a speaker. The author also tells about the discovery of nanotubes - the main component of nanoradio – and its unique properties, like exceptional strength and excellent conductivity. The experiments, which led to nanoradio invention, are also given along with the history of development of conventional radio. The structure and operation methods of nanoradio and conventional radio are compared. The author also mentions, that the device performed all four radio functions simultaneously: it was an antenna, amplifier, demodulator and tuner. Different applications for this technology are given like hearing aids, cell phones and iPods small enough to fit into the ear canal, or radio controlled drug delivery system, that would fit into a living cell and use drugs to kill cancer cells, or a small explosive-sensing mass spectrometers.

Plan.

1. Reality of nanotechnology
2. Nanotubes
3. Theory of nanoradio
4. Working prototypes
5. Applications of nanoradio

New words.

Static – помехи

Nanotube – нанотрубка

Demodulator – демодулятор

Rectification – выпрямление

Tip – конец

Needle – игла

Cancer cells – раковые клетки

Hello, my name is Lashkov Vladimir. I am a student of MIPT. Today I'd like to tell you about nanoradio. My presentation will take about 7 minutes. A lot of people are talking about nanotechnologies these days, but I will tell you about the real application. If you have any questions, I'll be pleased to answer them. **I've divided my talk into five parts:**

- Reality of nanotechnology
- Nanotubes
- Theory of nanoradio
- Working prototypes
- Applications

First, I'd like to talk about the reality of nanotechnology today. Nanotechnology is arguably one of the most overhyped "next big things" in the recent history of applied science. According to its most radical advocates, nanotechnology is a molecular manufacturing system that will allow us to fabricate objects of practically any arbitrary complexity by mechanically joining molecule to molecule, one after another, until the final, atomically correct product emerges before our eyes. The reality has been somewhat different: today the word "nano" has been diluted to the point that it applies to essentially anything small, even down to the "nanoparticles" in commodities as diverse as motor oil, sunscreen, lipstick and ski wax. Who, then, would have expected that one of the first truly functional nanoscale devices—one that would have a measurable effect on the larger, macroscale world—would prove to be ... a radio? prove to be ... a radio? But the nanotube radio, invented in 2007 by physicist Alex Zettl and his colleagues at the University of California, Berkeley, performs a set of amazing actions.

Let's move on to my second point, which is nanotubes. They are remarkable structures. The question of who irst discovered them is controversial, but Japanese physicist Sumio Iijima is generally credited with having put them on the scientiic map, when in 1991 he announced inding "needlelike tubes" of carbon on the tip of a graphite electrode that emitted an arc, a luminous discharge of electricity. **It's worth to mention that** ehose nanotubes had some surprising properties. Common to them all was their exceptional tensile strength, the resistance to being pulled apart along their length without breaking. Nanotubes are also excellent conductors of electricity, far better than copper, silver or even superconductors. It's because the electrons don't hit anything.

I'd like to move on to my third point and talk about the theory of nanoradio. During the course of some experiments aimed at producing a nanotube mass sensor, one of Zettl's graduate students, Kenneth Jensen, found that if one end of a carbon nanotube was planted on a surface, the beam would vibrate when a molecule landed on its free end. Molecules of different masses would make the beam vibrate at different frequencies. When Zettl noticed that some of these frequencies included those in the commercial radio band, the idea of using the cantilevered nanotube to make a radio became virtually irresistible.

A common radio has four essential parts: an antenna that picks up the electromagnetic signal; a tuner that selects the desired frequency from among all those being broadcast; an amplifier that increases the strength of the signal; and a demodulator that separates the informational signal from the carrier wave on which it is transmitted. The informational component is then sent to an external speaker, which turns that part of the signal into audible tones. The carbon nanotube that was to be the core of the device proved to be a combination of such extremely favorable chemical, geometric and electrical properties that when it was placed between a set of electrodes, the miniature element alone accomplished all four functions simultaneously. No other parts were needed. The idea was that electromagnetic waves from an incoming radio transmission would impinge on the nanotube, causing it to physically vibrate in tune with the variations of the electromagnetic signal. Vibrating in sync with the incoming radio waves, the nanotube would be acting as an antenna but one that operates differently from that of a

conventional radio. **It's worth to say that,** in a normal radio, the antenna picks up incoming signals electronically, meaning that the incoming waves induce an electric current within the antenna, which remains stationary. In the nanoradio, in contrast, the nanotube is light charged object that the incoming electromagnetic waves are sufficient to move it mechanically.

Let's move on to the next point – working prototypes. That, anyway, was the theory. In January 2007 the actual experiment was performed. Carbon nanotube was mounted on a silicon electrode about a micron away from counterelectrode. A DC battery was also attached to the apparatus to set up a small field-emission current between the nanotube tip and the counterelectrode. To actually see what would happen during the course of a radio transmission from a nearby antenna, they placed their device inside a high-resolution transmission electron microscope (TEM). Then they started broadcasting. Shortly after their initial success the experimenters removed the device, made minor changes to the radio's coniguration, and then were able to both broadcast and receive signals across the length of the laboratory, a distance of a few meters. They were also able to tune in different frequencies in real time, by changing an applied electric field.

Now I'd like to move on to my last point, which is applications of nanoradio. This technology makes possible to a whole new generation of communications devices, brain and muscle implants, and so on. Scientists are also working on a technology, which would allow to destroy cancer cells by injecting packages, containing nanoradios. No one is commercializing any of these devices as yet. Zettl, however, has patented his nanoradio, the nano mass sensor and other inventions that have come out of his Center of Integrated Nanomechanical Systems and has begun licensing the technology for others to develop.

That is about all. But before I close, I'd like to remind you the most important aspects of my presentation:

1) Nanoradio is based on the nanotube, which performs all the functions of the conventional radio
2) Extremely small size of nanoradio allows to use it in new applications.

Thank you for your attention and I,m ready to answer your questions.

THE WORLD'S SMALLEST Radio

BY ED REGIS

A single carbon nanotube can function as a radio that detects and plays songs

KEY CONCEPTS

- Nanotechnology has demonstrated more hyperbole than substance for many years—and the "nano" label has been applied to items ranging from motor oil to lipstick.
- One of the first true nanoscale machines is a radio that can play songs such as Eric Clapton's "Layla" and the theme from *Star Wars*.
- A single nanotube in this device performs the function of multiple components in larger radios. The nanoapparatus may ultimately find uses in drug delivery devices, prosthetics or explosives detectors.

—*The Editors*

Nanotechnology is arguably one of the most overhyped "next big things" in the recent history of applied science. According to its most radical advocates, nanotechnology is a molecular manufacturing system that will allow us to fabricate objects of practically any arbitrary complexity by mechanically joining molecule to molecule, one after another, until the final, atomically correct product emerges before our eyes.

The reality has been somewhat different: today the word "nano" has been diluted to the point that it applies to essentially anything small, even down to the "nanoparticles" in commodities as diverse as motor oil, sunscreen, lipstick and ski wax. Who, then, would have expected that one of the first truly functional nanoscale devices—one that would have a measurable effect on the larger, macroscale world—would prove to be ... a radio? But the nanotube radio, invented in 2007 by physicist Alex Zettl and his colleagues at the University of California, Berkeley, performs a set of amazing feats: a single carbon nanotube tunes in a broadcast signal, amplifies it, converts it to an audio signal and then sends it to an external speaker in a form that the human ear can readily recognize. If you have any doubts about this assertion, just visit www.SciAm.com/nanoradio and listen to the song "Layla."

The nanotube radio, its fabricators say, could be the basis for a range of revolutionary applications: hearing aids, cell phones and iPods small enough to fit completely within the ear canal. The nanoradio "would easily fit inside a living cell," Zettl says. "One can envision interfaces to brain or muscle functions or radio-controlled devices moving through the bloodstream."

The Call of the Nanotube

Zettl, who directs 30 investigators engaged in creating molecular-scale devices, decided to make nanotubes a focus of his work because they are remarkable structures. The question of who first discovered them is controversial, but Japanese physicist Sumio Iijima is generally credited with having put them on the scientific map, when in 1991 he announced finding "needlelike tubes" of carbon on the tip of a graphite electrode that emitted an arc, a luminous discharge of electricity.

Those nanotubes had some surprising properties. They came in a large variety of sizes and shapes: they were single-walled, double-walled and multiwalled. Some were straight, some were bent and some even looped back on themselves in toroidal configurations. Common to them all was their exceptional tensile strength, the resistance to being pulled apart along their length without breaking. The reason for this unusual property, Zettl says, is that "the force that holds the carbon atoms together in the carbon nanotube is the strongest bond in nature." Nanotubes are also excellent conductors of electricity, far better than copper, silver or even superconductors. "It's because the electrons don't hit anything," he explains. "The tube is such a perfect structure."

Zettl got the idea for a nanoradio when he decided he wanted to create tiny sensing devices that could communicate with one another and broadcast their observations wirelessly. "They were to do monitoring of environmental conditions," he says. They would be distributed in the field near some factory or refinery and would radio their results back to some collecting point. Anyone could then go to Google "and click on the air quality of a city and see it in real time."

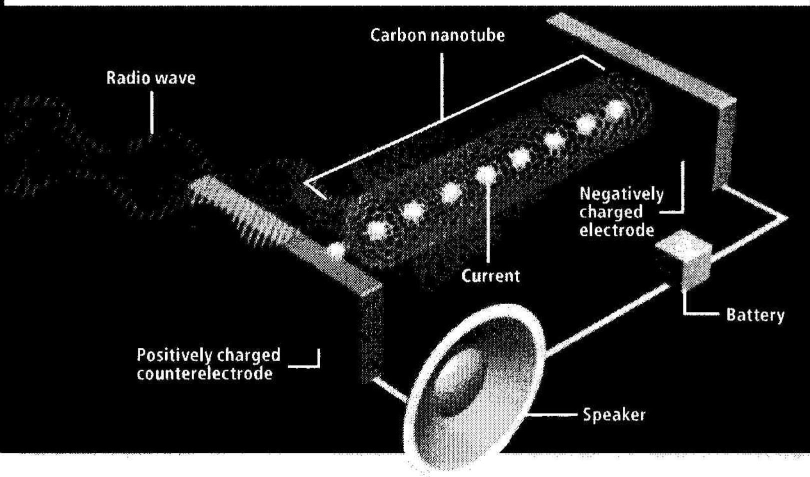
SHELTER PRODUCTIONS (*photo*); KURSTEN BRACCHI (*prop styling*); ANTHONY LAMBERT FOR HALLEY RESOURCES (*grooming*)

[GOOD VIBRATIONS]

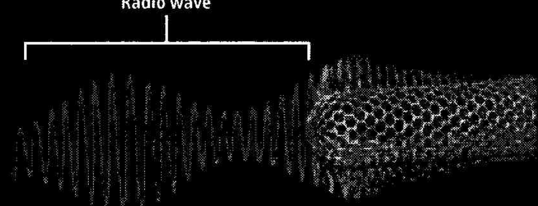
Anatomy of the Tiniest Radio

Just one nanotube can perform all the functions of a standard radio with many parts. Its tiny dimension enables it to vibrate rapidly in the presence of a radio signal. Connected to an electrical circuit, this nanoantenna can then be tweaked to tune, amplify and isolate just the audio component from the rest of the radio wave so that the sounds of the Beach Boys or George Frideric Handel can be discerned.

NANOTUBE RADIO



RECEPTION



Antenna of nanodimensions detects a radio wave by vibrating at the same frequency as the rapidly oscillating signal.

During the course of some experiments aimed at producing a nanotube mass sensor, one of Zettl's graduate students, Kenneth Jensen, found that if one end of a carbon nanotube was planted on a surface, creating a cantilever, the beam would vibrate when a molecule landed on its free end. Molecules of different masses would make the beam vibrate at different frequencies. When Zettl noticed that some of these frequencies included those in the commercial radio band, the idea of using the cantilevered nanotube to make a radio became virtually irresistible.

A bare-bones radio, Zettl knew, has four essential parts: an antenna that picks up the electromagnetic signal; a tuner that selects the desired frequency from among all those being broadcast; an amplifier that increases the strength of the signal; and a demodulator that separates the informational signal from the carrier wave on which it is transmitted. The informational component is then sent to an external speaker, which turns that part of the signal into audible tones.

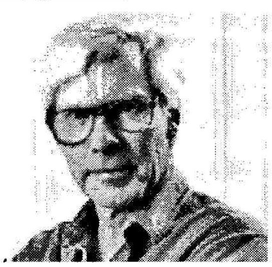
The carbon nanotube that was to be the core of the device proved to be a combination of such extremely favorable chemical, geometric and electrical properties that when it was placed between a set of electrodes, the miniature element alone accomplished all four functions simultaneously. No other parts were needed.

Zettl and Jensen began by working out an overall design in which a multiwalled carbon nanotube would be built on the tip of an electrode, an arrangement in which the nanotube would resemble a flagpole on a mountaintop. They decided on a multiwalled tube because it was a bit bigger than other kinds and was also easier to mount on the electrode surface, although they later constructed a version with a single-walled one as well. The tube, which would be about 500 nanometers long and 10 nanometers in diameter (roughly the size and shape of some viruses), would be placed on the electrode using nanomanipulation methods or directly grown on the electrode by a technique called chemical vapor deposition, in which layers of carbon precipitate out of an ionized gas.

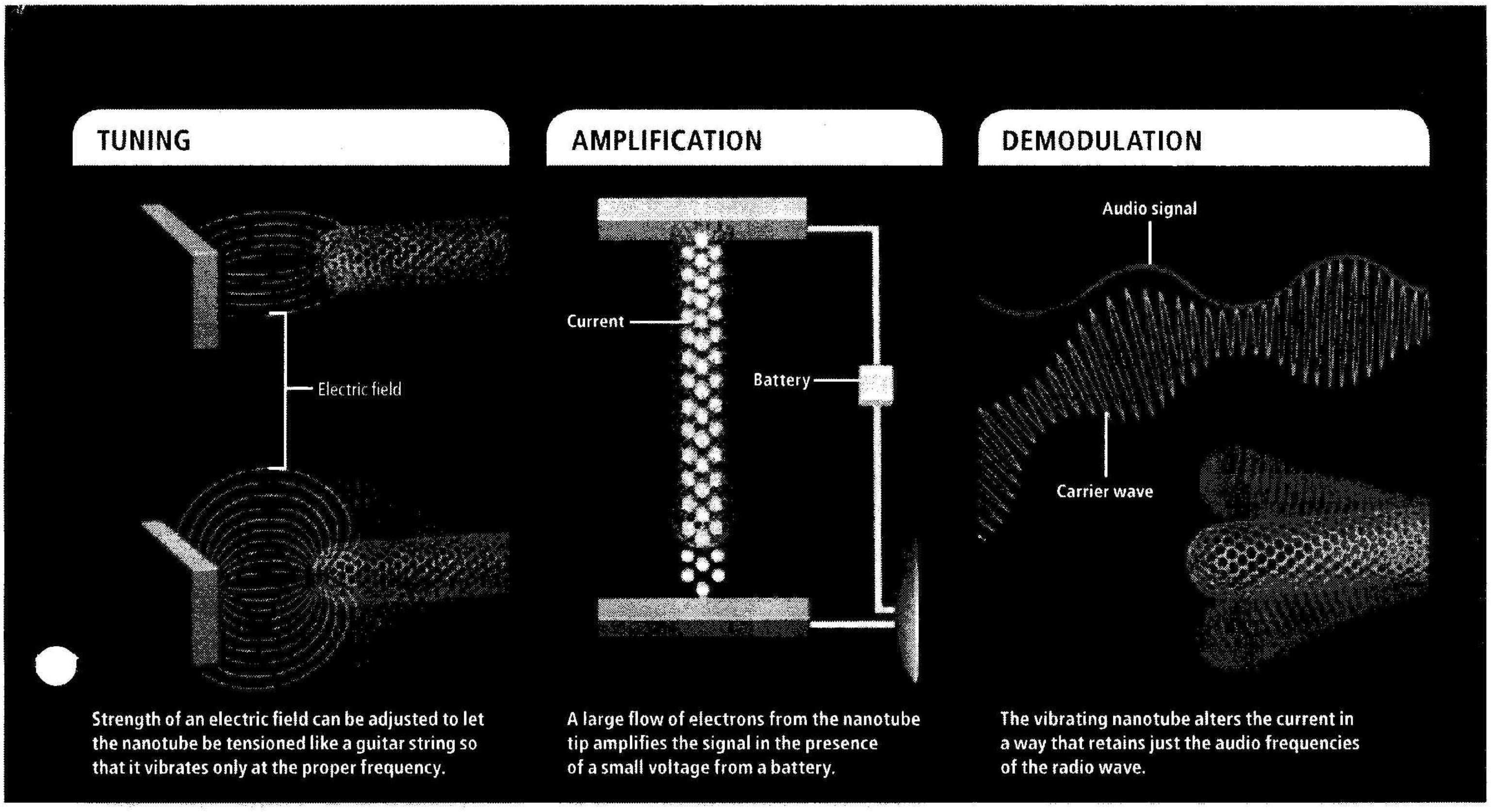
Some distance away from the tip, rounded off in the shape of a hemispherical buckyball, would be a counterelectrode. A small direct-current (DC) voltage would be applied across the electrodes, creating a flow of electrons from the nanotube tip to the counterelectrode. The idea was that electromagnetic waves from an incoming radio transmission would impinge on the nanotube, causing it to physically vibrate in tune with the variations of the electromagnetic signal. Vibrating in sync with the incoming radio waves, the nanotube would be acting as an antenna but one that operates differently from that of a conventional radio.

In a normal radio, the antenna picks up incoming signals electronically, meaning that the incoming waves induce an electric current within the antenna, which remains stationary. In the nanoradio, in contrast, the nanotube is so slen-

[THE AUTHOR]



Ed Regis has written seven science books, including the recent *What Is Life?: Investigating the Nature of Life in the Age of Synthetic Biology*, which is about the attempt to build an artificial living cell. He and his wife live in the mountains in Maryland near Camp David.



Strength of an electric field can be adjusted to let the nanotube be tensioned like a guitar string so that it vibrates only at the proper frequency.

A large flow of electrons from the nanotube tip amplifies the signal in the presence of a small voltage from a battery.

The vibrating nanotube alters the current in a way that retains just the audio frequencies of the radio wave.

der and slight a charged object that the incoming electromagnetic waves are sufficient to push it back and forth mechanically.

"The nanoworld is weird—different things dominate," Zettl describes. "Gravity plays no role whatsoever, and inertial effects are basically nonexistent because things are just so small that residual electrical fields can play a dominant role."

The nanotube's vibrations, in turn, would set up a change in the current flowing from the nanotube tip to the counterelectrode: technically a field-emission current. Field emission is a quantum-mechanical phenomenon in which a small applied voltage produces a large flow of electrons from the surface of an object—a needle tip, say. Because of the way field emission works, the nanotube was expected to function not only as an antenna but also as an amplifier. The small-scale electromagnetic wave hitting the nanotube would cause a big spray of electrons to be released from its vibrating free end. That electron spray would amplify the incoming signal.

Next came demodulation, the process of separating a radio station's carrier-wave frequency from the informational message—voice or music—that is coded on top of it. In an amplitude-modulation (AM) radio broadcast, for example, this separation is achieved by a rectification and filtering circuit that responds to the amplitude and ignores (filters out) the frequency of the carrier-wave signal. These functions, too, Zettl's team reasoned, could be accomplished in the nanotube radio: when a nanotube mechanically vibrates in tune with a carrier wave's frequency, it also responds to the coded informational wave. Fortunately, rectification is an inherent attribute of quantum-mechanical field emission, meaning that the current coming off the nanotube varies only with the coded or modulated informational wave, whereas the carrier wave drops out of the picture. It would be demodulation for free—no separate circuitry required.

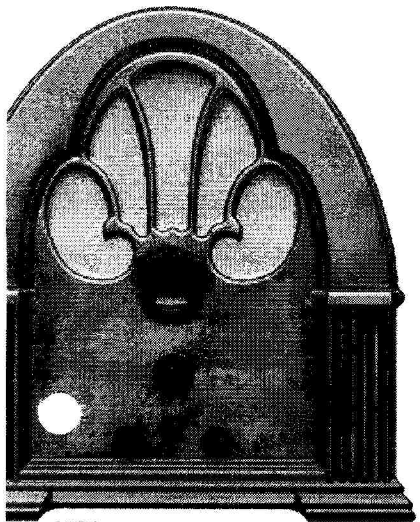
In short, an incoming electromagnetic signal would cause the nanotube, now acting as an antenna, to vibrate. Its vibrating end would amplify the signal, and its field-emission property of built-in rectification would separate (or demodulate) the carrier wave from the informational wave. The counterelectrode would then detect the changes in the field-emission current and send a song or news broadcast to an audio loudspeaker, which would convert the signal into sound waves.

Doing the Experiment

That, anyway, was the theory. In January 2007 Zettl, Jensen and two other Berkeley researchers, Jeff Weldon and Henry Garcia, performed the actual experiment. They mounted a multiwalled carbon nanotube on a silicon electrode and placed a counterelectrode about a micron away, connecting the two by wire. They also attached a DC battery to the apparatus to set up a small field-emission current between the nano-

The working element of the radio would be the size and shape of some viruses.

VANISHING RADIOS



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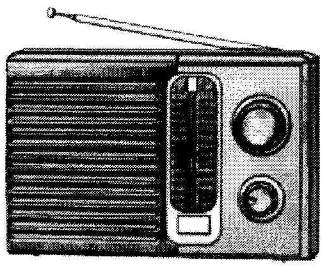

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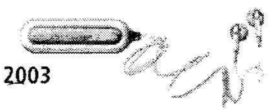
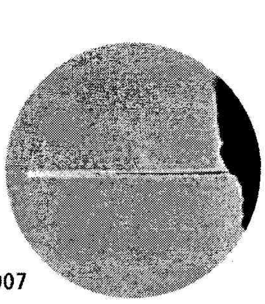


2003



2007

Radio waves are invisible, and now radios are, too, shrinking from a big box down to the size of a vibrating needlelike nanotube that can be viewed only through a high-powered microscope.

tube tip and the counterelectrode. To actually see what would happen during the course of a radio transmission from a nearby antenna, they placed their device inside a high-resolution transmission electron microscope (TEM). Then they started broadcasting.

According to the well-worn tale, the first message sent by telephone was the request, "Mr. Watson, come here. I want to see you," spoken by Alexander Graham Bell in 1876. The first wireless transmission, sent by Guglielmo Marconi in 1894, was a radio wave that made a bell ring 30 feet away. And in January 2007 the first successful operation of Zettl's carbon nanotube radio was the radio's reception of the music for "Layla," by Eric Clapton (while playing with Derek and the Dominos).

"It was fantastic," Zettl recalls of the experience. "I mean, it was spectacular. We could watch the nanotube [in the TEM], and the fact that you could see this molecular structure vibrating and hear it at the same time is kind of cool. I never thought I could *see* a radio operate!"

You can see the results for yourself, because the experimenters documented the entire process—audio and video—and converted the recording to a QuickTime movie that they posted on the Zettl Group's Web page, where anyone can download and play it for free. Later, they did the same with "Good Vibrations," by the Beach Boys; the "Main Title" theme from *Star Wars*, by John Williams; and the largo from *Xerxes*, the opera by George Frideric Handel. "This is the first song ever transmitted using radio," Zettl explains.

Hearing (and, yes, even watching) these tunes play is a surreal experience to witness. As the process starts up, a long, thin stationary nanotube appears against a featureless, grainy backdrop. The tube extends horizontally from a rocky-looking, irregular surface, next to a shorter nanotube that will remain untouched throughout by all the electromagnetic commotion taking place around it. (The shorter nanotube is insensitive to the broadcast because the frequency at which it resonates, which depends on its length, does not coincide with the frequency of the incoming transmission.)

Soon you hear a lot of static, but then the needle simply disappears in a vibrational blur as the song in question is dimly but recognizably heard above the background noise. It may sound like a broadcast from Neptune, but in fact it is the audible report of a countable number of carbon atoms moving in synchrony with the music.

Shortly after their initial success the experimenters removed the device from the TEM, made minor changes to the radio's configuration, and then were able to both broadcast and receive signals across the length of the laboratory, a distance of a few meters. They were also able to tune in different frequencies in real time, in effect "changing the station" as the radio played.

A nanotube radio can be tuned in two separate ways. One is by changing its length. While you can change the tone of a guitar string by bending it down against different frets, you can change the resonance frequency of a nanotube by shortening it—for example, by boiling atoms off the tip.

That, change, however, is irreversible. But just as there is a second method of varying a guitar string's pitch (namely, by varying its tension), so, too, with the nanotube. Varying the strength of the applied electric field will make the nanoradio respond to different frequencies of the radio band.

Their device did, in fact, perform all four of a radio's functions simultaneously: it was an antenna, amplifier, demodulator and tuner—all in one. That such a small and simple structure combined all these functions continues to amaze Zettl. How does he explain their almost magical convergence in a single elongated molecule of carbon?

"In electronics, often you have a trade-off: if you optimize this, then you lose something else. Here everything seems to just work for you, which is a little unusual. You don't see that often in science. It's one of those rare opportunities to see Murphy's Law not rearing its ugly head. Here everything that can go right is going right," he says.

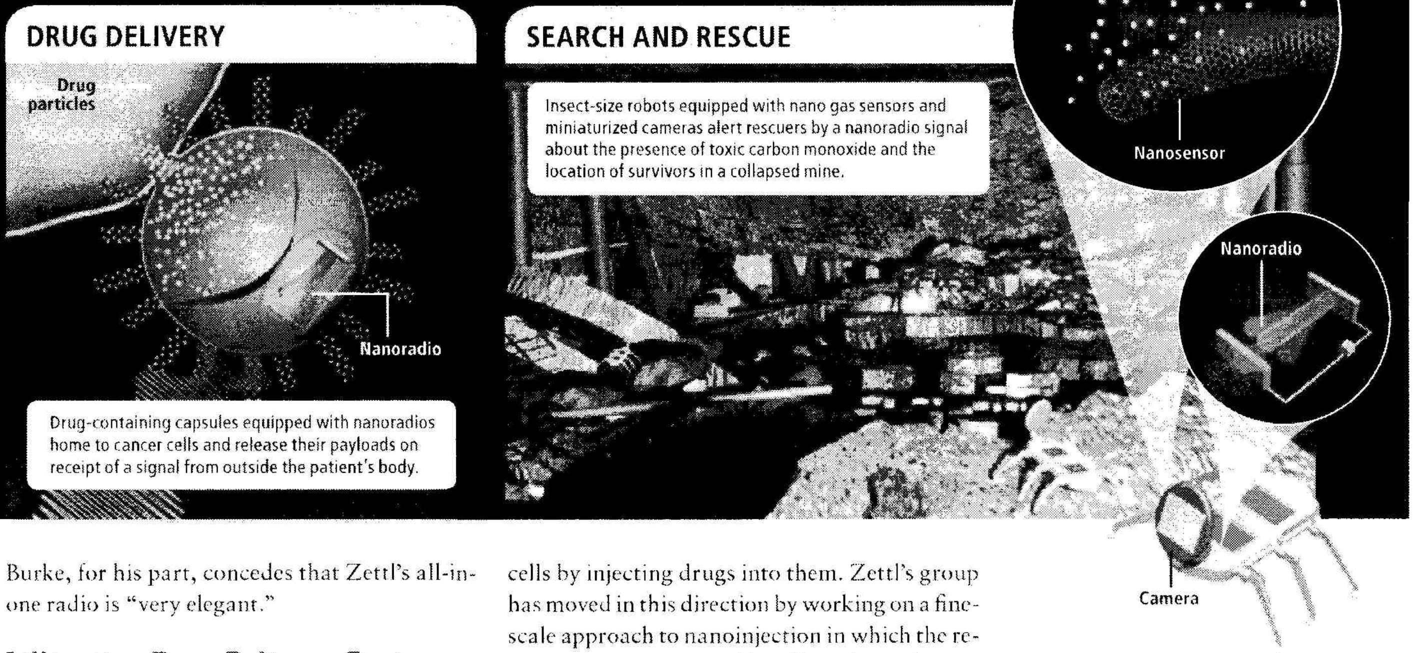
Zettl and his colleagues withheld news of the nanoradio for several months, until it could be published in *Nano Letters*, a journal of the American Chemical Society. The apparatus had its formal debut online in October 2007 and then in the November print edition. In that same print issue, two independent researchers, Chris Rutherglen and Peter Burke, both at the University of California, Irvine, announced the use of a carbon nanotube to demodulate an AM signal. They called their piece "Carbon Nanotube Radio," but their radio was not an all-in-one device like Zettl's. In Rutherglen and Burke's setup, the antenna and amplification functions were provided by conventional, life-size desktop units.

HEATHER GORDON (*vacuum tube radio, transistor radio and digital radio*); COURTESY OF ZETTL RESEARCH GROUP, LAWRENCE BERKELEY NATIONAL LABORATORY AND UNIVERSITY OF CALIFORNIA, BERKELEY (*nanoradio*)

[MORE THAN A TOY]

What to Do with a Radio You Can't See

The nanoradio is not just an alluring graduate project. The ability to send and receive signals from a microscopic apparatus will enable development of radically new types of drug delivery devices and robots that can assist in rescues at disaster sites.



GEORGE RETSECK

Burke, for his part, concedes that Zettl's all-in-one radio is "very elegant."

Lilliputian Drug Delivery Systems

Because it turns nanotechnology from a collection of theories, hopes and speculations into a practical, working appliance, the nanotube radio is potentially a transformative piece of equipment. Zettl, for one, is not bashful about foreseeing a bunch of killer apps made possible by the nanoradio: a whole new generation of communications devices, brain and muscle implants, and so on. Whereas some of these more futuristic applications will require a nontrivial amount of additional insight and engineering to make them into operational realities, others are more near term—in the form of radio-controlled drug delivery systems, for example.

One of the downsides of chemotherapy for shrinking invisible cancers that have spread or for treating inoperable ones is that the chemical agents used to kill cancer cells travel through the bloodstream to all parts of the body and often kill healthy cells as well as the malignant ones. A solution advanced by some physicians who have been in contact with Zettl would be to first inject packages that are molecularly targeted to cancer cells and that contain a chemo agent as well as a nanoradio; after allowing the packages time to find the tumors, radio-control signals would trigger release of the drug into the tumor cells for their destruction.

A second use would be to repair individual cells by injecting drugs into them. Zettl's group has moved in this direction by working on a fine-scale approach to nanoinjection in which the researchers punctured cell walls and membranes and put nanotube structures inside, where they released specific chemicals.

"The cells withstand that very nicely," Zettl says. "This nanoinjection technique works much better than the old technique where people used to try to use micropipettes that puncture cells and inject fluid. Those are way too crude and disruptive for most living cells." Zettl also foresees an application of his original nanotube mass sensor. Some types of explosives contain signature molecules of a known mass, and so a minuscule instrument that detects those molecules rapidly and reliably could replace the refrigerator-size explosives-sensing mass spectrometers now in use at some airport security checkpoints. No one is commercializing any of these devices as yet. Zettl, however, has patented his nanoradio, the nano mass sensor and other inventions that have come out of his Center of Integrated Nanomechanical Systems and has begun licensing the technology for others to develop.

Perhaps not surprisingly, some of Zettl's more recent achievements in the nanoworld seem to have plumbed the very limits of the Lilliputian. In July 2008 he announced in *Nature* that he and his group had coaxed an electron microscope to image individual atoms of hydrogen, nature's smallest atom. In the downward direction, there is nowhere left to go. ■

➡ MORE TO EXPLORE

Nanotube Radio. Alex Zettl et al. in *Nano Letters*, Vol. 7, No. 11, pages 3508–3511; 2007.

An Atomic-Resolution Nanomechanical Mass Sensor. Alex Zettl et al. in *Nature Nanotechnology.* Published online on July 20, 2008.

Images and movies of the University of California, Berkeley, group's nanotube radio can be found at **www.physics.berkeley.edu/research/zettl/projects/nanoradio/radio.html**